Patent Application of

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for

CONVERTER FOR ELECTRONIC FLASHLIGHT

Background--Field of Invention

The present invention relates generally to battery-powered lights, and more particularly to d.c.-to-d.c. converters designed to supply power to a light-emitting diode (LED).

Background--Description of Prior Art

LEDs are extremely promising as a way to make robust, long-lasting, efficient light sources. Unlike ordinary incandescent bulbs, LEDs cannot be simply connected to a low-impedance battery, but need some form of driver circuit or current limiting. Additionally, the most common and economical single cells--1.5v alkaline cells--do not produce adequate voltage to power, for example, a white GaN LED with a forward drop of 2.8 volts. Thus, the subject of making LED flashlights and the construction of dc-to-dc converters for this purpose has fascinated the public for some time.

D.C.-TO-D.C. CONVERTER FUNDAMENTALS

D.C.-to-D.C. converters are used to transform an available voltage source, such as a battery, to a desired voltage, such as the forward voltage Vf of a light emitting diode (LED). "Switching" converters commonly do this by storing energy into an inductor during an "on" time tON, and allowing that inductor to discharge into the load during an "off" time tOFF. "OFF" and "ON" refer to the state of the main power switching element, commonly a transistor, that applies the charging potential to the inductor.

CONTINUOUS AND DISCONTINUOUS MODES

A continuous mode dc-to-dc converter is so-called if current flows at all times--i.e., *continuously*--in the flyback inductor. This objective is achieved by terminating the flyback interval before the inductor has been fully discharged. When a converter's inductor is allowed to fully discharge during the off interval, this is known as *discontinuous* mode. In all cases, energy from the input supply is stored into the inductor during the "on" time, and removed (discharged into the load) during the flyback interval, or "off" time.

To illustrate the distinction, Fig. 5 depicts a simplified boost converter. During each "on" time period tON switching transistor **Q500** is driven ON, grounding one side of inductor **L500**. The other side of inductor **L500** is connected to supply voltage **Vcc**. To a first approximation, the current **iL** flowing in inductor **L500** increases during time period tON according to

$$\Delta \mathbf{iL} = \mathrm{tON} \bullet \mathbf{Vcc} / \mathrm{L}. \text{ (Eq. 1)}$$

When tON ends the inductor **L500** begins to discharge into the load, LED **D500**. At the end of time period tOFF the current **iL** in inductor **L500** will have decayed to:

$$\mathrm{iL} = \mathrm{iL}_0 - \mathrm{tOFF} \bullet \mathrm{Vdischg} / \mathrm{L} \text{ (Eq. 2)},$$

where Vdischg is the voltage across the inductor as it is discharged. In this case Vdischg is set by and is equal to the forward voltage of the load, LED **D500**.

If tOFF is long enough for the inductor **L500** to fully discharge (iL = 0), then the converter is said to be operating in "*discontinuous mode*," referring to the non-continuous current flowing in inductor **L500**. Fig. 6a is an illustration of the current waveform in inductor **L500** when operating in discontinuous mode.

If tOFF ends (and tON commences) before inductor **L500** has fully discharged, then some current iL ≠ 0 remains that will be added to during the next "on" cycle. As current is always flowing in inductor **L500** the converter is termed a "*continuous mode*" converter. Fig. 6b depicts the current waveform in inductor **L500** when operating in continuous mode.

RUNAWAY AND THE NEED FOR LIMITING

Note that if more current is added to inductor **L500** with each "on" cycle tON than is discharged during tOFF, then inductor current iL will increase with each cycle until the limit of the switching transistor **Q500**, inductor **L500**, or some other circuit element is reached. This circumstance is ordinarily avoided in prior art circuits by use of feedback, inductor-current sensing schemes, or both, to regulate tON so as to maintain a desired range of currents in inductor **L500**.

DISCUSSION OF THE PRIOR ART

HORTON

Horton[1] discloses how to make an LED flashlight from an existing flashlight. Horton's device comprises a constant voltage output boost/buck converter using a commercial integrated circuit, to be installed inside the flashlight. Current limiting to the LEDs is ensured by a 4.7 ohm resistor.

STIRLING

Stirling[2-5] discloses construction of a prototype LED flashlight using a single AAA cell. An existing flashlight was retrofitted[2,3]: the bulb was replaced with an LED, and a voltage-boosting converter was installed inside the flashlight casing to power the LED. Stirling's boost converter used a two-transistor multivibrator to drive a third transistor, the third transistor being a switch used to drive an inductor.[4][5]

DUTCHER

Dutcher[6] discloses a dc-coupled multivibrator whose off-time is equal to the discharge time of the inductor, and whose "on"-time is set by the point where the main power-switching transistor pops out of saturation. The Dutcher circuit's power supply voltage-compensation relies on a strategy of increasingly starving the switching transistor--causing it to pop out of saturation earlier than it otherwise would have, abbreviating the on-interval and reducing the converter's power output. Starved base drive, however, does not saturate the switching transistor optimally, resulting in a significant loss of power-conversion efficiency. The drive circuit disclosed also ensures that the switching transistor will still be fully on for the first portion of flyback, producing significant switching losses.

The Dutcher circuit's "on" timing is controlled by a current limit on the power-switching transistor's conduction current. Dutcher does not set on-time with timing components, nor stabilize the output power with a variable timing current into a capacitor. This "on"-time control strategy makes the circuit's output directly dependent on both the power-switching transistor Q2's [6] gain/saturation characteristics. These dependencies make the circuit difficult to reproduce in quantity while maintaining the intended output power and stability. Transistor gains routinely vary over a 2:1 range from unit-to-unit, for example, directly affecting the circuit's on-time -- and thus its power output -- and the illumination level of the flashlight. The manufacturer's specification for the 2n3904 used in Dutcher's circuit, for example, states that its gain can range from 100-to-300 at 10mA to less than 1/8th those values at 200mA. Transistor gains also suffer from shifts with changes in temperature. These factors combine to make the ultimate power output of the Dutcher circuit difficult to control.

Dutcher's circuit can also be designed such that the on-interval is terminated by allowing the inductor to saturate and pop the switching transistor out of saturation. Both this and the starved-transistor method result in high switching losses and high susceptibility to secondary characteristics of the components, e.g. inductor saturation current, V_{sat} and h_{fe} of the switching transistor, and change of same with temperature.

WENER

An astable multivibrator, such as in Fig. 1a, comprises two monostable pulse generators, each driving the other. The monostables' timings are set by separate resistor-capacitor (R-C) time constants. If **R1A** << **R2A** and **R4A** <<

R3A then **R2A*C1A** controls the "off" time tOFF, and **R3A*C2A** controls the "on" time tON of output transistor **Q2A**. Fig. 2a is a diagram showing the circuit's functional blocks.

With a minimum of change, an ordinary astable multivibrator (Fig. 1a) can be pressed into service as a dc-to-dc converter. Wener et al.[7] disclose a single-cell LED flashlight employing an internal voltage boosting converter wherein one of the collector load resistors **R4A** of Fig. 1a is replaced with inductor **L1B** to produce Fig. 1b, a boost-converter. As with Fig. 1a, **R2B*C2B** sets tOFF and **R3B*C2B** controls tON. The result is a boost converter comprising two R-C controlled monostable pulse generators, each triggering the other, where one of these also drives an inductor as a load. tON and tOFF are set by the RC networks, not the inductor. Fig. 2b summarizes the circuit's function in block-diagram form.

The Wener converter is not regulated. Instead, the circuit shifts from discontinuous to continuous mode as supply voltage **Vcc** rises, adding current into inductor **L1B** with each cycle. The current in inductor **L1B** then quickly increases to high levels, the circuit becomes inefficient, and the final result is a power output that varies strongly with battery voltage.

These difficulties can be understood as follows: in Fig. 1B the timing currents controlling tON and tOFF flow into timing capacitors **C2B** and **C1B**, respectively, and are set by resistors **R3B** and **R2B**, respectively. As supply **Vcc** increases both timing currents increase, decreasing both tON *and* tOFF. During tOFF, tON timing capacitor **C2B** is charged to the flyback voltage less Vbe(**Q1B**), typically 3.4volts. By contrast the tOFF timing capacitor **C1B** is charged only to **Vcc** - Vbe(**Q2B**), typically 1.3V-0.6V = 0.7 volts with a moderately used single alkaline cell providing supply voltage **Vcc**. Because the off-timing resistor **R2B** has a much lower voltage across it than resistor **R3B**, small absolute changes in supply voltage **Vcc** produce greater percentage changes in the timing current resistor that **R2B** generates. tOFF thus decreases more rapidly than tON, which, unfortunately, increases the converter's on-to-off duty cycle. Meanwhile, the time needed to fully discharge inductor **L1B** *increases* with supply voltage **Vcc** according to:

$$tOFF = i(\mathbf{L1B}) \bullet \mathbf{L1B} / [Vf(D1B) - \mathbf{Vcc}].$$

tOFF, therefore, is decreasing as **Vcc** rises, which is the opposite of what's desired. The result is that, at some intermediate value of voltage **Vcc**, tOFF becomes too short to allow full discharge of inductor **L1B**. The converter enters continuous mode, and thereafter inductor **L1B** current rises very rapidly with **Vcc**. The power delivered to the load increases even more rapidly as additional energy is pumped into the boost inductor even as the need for that boost energy is decreasing. Since inductor **L1B** doesn't have time to fully discharge, its standing current rises with each successive switching cycle until switching transistor **Q2B** can no longer switch the excessive current. Thereafter, tON is curtailed when transistor **Q2B** pops prematurely out of saturation. Inductor **L1B** then flies back while transistor **Q2B** is still fully conducting, producing excessive dissipation / waste in transistor **Q2B**. At high current and flyback voltage levels, such as when driving multiple LEDs, transistor **Q2B** may be destroyed. A

further disadvantage is that the illumination level from the LED falls off precipitously with falling supply voltage Vcc, before the battery has been fully utilized.

A third related problem stemming from this transition to continuous mode is sensitivity to component values: as the output power is highly dependent on the tON and tOFF selected, input voltage, and duty cycle, small changes in component characteristics will affect the point where the converter enters runaway / continuous mode, producing large variations in said output power.

Fig. 4 plots actual measurements of the input-current vs: battery-voltage responses of Wener and the instant invention. Curve **401**. depicts the Wener circuit's (Fig. 1B) performance, showing the rapid increase in input current with increasing supply voltages, resulting in an output power that increases exponentially with battery voltage. From 0.75v to 1.55v the Wener circuit's input power varies over a ratio of 33:1. Additionally, at higher supply voltages **Vcc** the circuit is grossly inefficient.

PRIOR ART OUTPUT STABILIZATION

In prior art converters, inductor current and output power are usually controlled by the use of feedback circuitry to sense and control the switch current, output voltage or current, or a combination of these. The feedback system then adjusts the switch's duty cycle to maintain the desired output.

Prior art continuous mode circuits *must* have some sort of feedback to prevent the inductor's standing current from increasing each cycle until the inductor--or the switching transistor driving it--saturates out of control. One of several common feedback techniques is to sense the inductor's charging current on a cycle-by-cycle basis and adjust the "on"-time to hold this peak current below a certain target value. As the battery voltage changes, so must the duty factor of the boost circuit. Such circuits add to the cost and complexity of a converter.

[1] 4/19/95 "Re: LED Flashlight", Kevin Horton, sci.electronics

[2] 3/17/97 "Re: Mini-Maglite Alternatives", Ian Stirling, misc.survivalism

[3] 3/21/97 "LED brightness", Ian Stirling, sci.electronics.design

[4] 3/22/97 "Re: Mini-Maglite Alternatives", Ian Stirling, misc.survivalism, message 199703220548.FAA20600.mauve.demon.uk

[5] 3/22/97 "Re: Mini-Maglite Alternatives", Ian Stirling, misc.survivalism, message 199703220551.FAA22127.mauve.demon.uk

[6] 6/18/01 "Single-cell flashlight uses any type of LED", Al Dutcher, Electronic Design, 6/18/01, p162-3

[7] United States patent 6,366,028 B1

Brief Description of Drawing Figures

In the drawings, closely related figures have the same number but different alphabetic suffixes.

Fig. 1a. Multivibrator circuit diagram

Objects and Advantages

The present invention achieves numerous objects and advantages, including:

(a) to make an efficient converter capable of stepping up the output voltage of one or more cells so as to be able to power an LED having a forward voltage greater than said cells;

(b) to make a converter that transforms the voltage of one or more cells to drive an LED or LEDs with substantially constant power despite variations in the converter's input voltage supply;

(c) to make a converter that is capable of producing multiple selectable power outputs , thus permitting user selection between high-illumination and long battery life;

(d) to make a converter that is free from parts' sensitivities, and whose output is predictably set by non-critical components;

(e) to make a converter whose output power versus input voltage characteristic is easily customized.

Description of the Invention

The invention, depicted in Fig 1c., consists of an astable multivibrator-style oscillator comprising two transistors, cross-coupled with capacitors, where the collector load of one transistor has been replaced with an inductor, and the traditional timing capacitor to the base of this same transistor has been replaced with a relatively large-valued d.c. blocking capacitor instead.

For economy and simplicity, the preferred version of the invention uses a resistor to provide a timing current that varies with supply **Vcc**, yielding an output power characteristic that increases approximately linearly with **Vcc**, however more complicated timing current networks such as a resistor in series with a diode, or current sources, may be used to further reduce the variation of output power over changes in **Vcc** (e.g. Figs. 3a-e).

Operation of the Invention

START-UP

Referring to Fig. 1c, during initial startup the time constants ensure that resistor-capacitor timing network **R3C-C2C** charges first, driving transistor **Q1C** into a linear region of operation. **Q2C** base charges up to Vbe(**Q2C**) via **R2C** until **Q2C** conducts. At this point each transistor amplifies its own noise, producing an output. Said outputs are each coupled to the other transistor, amplified, then coupled back to the first transistor. The effect is regenerative and oscillation rapidly ensues.

D.c. blocking capacitor **Cinf** serves to allow startup with Vce(**Q1C**) < Vbe(**Q2C**), a condition where startup could otherwise fail with **Q1C** "on" and **Q2C** "off". If operation over a more limited supply voltage range is acceptable it is possible to eliminate **R2C** and **Cinf** by connecting the base of **Q2C** directly to the collector of **Q1C**. As a guideline, design calculations should be made to ensure that the timing current supplied by **R3C** (or other timing current generator) during startup is less than approximately [Vcc-Vbe(**Q2C**)]/[**R1C***hfe(**Q1C**)].

NORMAL OPERATION

Once oscillating, consider: when transistor **Q2C** switches off **L1C** will flyback, driving transistor **Q1C** into saturation while the magnetic field stored in **L1C** decays. When its flyback current decreases to zero, the voltage across **L1C** decays rapidly. The **C2C-L1C** node voltage falls, and with it the voltage at transistor **Q1C**'s base, biasing transistor **Q1C** into cutoff. Transistor **Q1C**'s collector voltage rises, biasing switch transistor **Q2C** "on" via blocking capacitor **Cinf**. Transistor **Q2C** stays on either until the timing current from **R3C** charges **C2C** to Vbe(**Q1C**), or until **Q2C**'s collector current through **L1C** exceeds the level supportable by transistor **Q2C**'s base current. When one of these terminating conditions is reached, transistor **Q2C**'s collector voltage abruptly rises, transistor **Q1C** is biased on, transistor **Q2C** is cut off, and the cycle repeats.

Optional rectifier **D1C** and filter capacitor **C3C** serve to filter the converter's output, providing direct-current drive for the LED **D2C**. If desired these can be omitted & the LED allowed to run on pulsating current present at the collector of **Q2C**.

It can bee seen that the present invention dispenses with the need for external feedback, setting a stabilized output power predictably by setting a single timing parameter -- tON -- with non-critical components. Specifically, changing the off-timing capacitor **C1B** of Fig. 1B to d.c.-blocking capacitor **Cinf**, transforms the astable multivibrator of Fig. 1b into the flyback-controlled converter of Fig. 1c. Like Fig. 1b, the new circuit's "on" time tON is also set by **R3C*C2C**, but unlike Fig. 1b, adjusting this one time-constant now provides a simple, single-point means of setting this converter's output power.

OUTPUT STABILIZATION ACTION

The new circuit's "off" time is controlled by the discharge / flyback time of inductor **L1C**. Inductor **L1C**'s discharge time, in turn, is proportional to its initial current, and inversely proportional to the voltage across it, i.e.

$$tOFF = iL \bullet \mathbf{L1C} / [Vf(\mathbf{D2C})+Vf(\mathbf{D1C}) - \mathbf{Vcc}]. \text{ (Eq. 3)}$$

This happy fact serves to stabilize the converter's output: when the input voltage (**Vcc**) is high and the flyback voltage across the inductor is reduced, tOFF is extended. The longer off-time, in turn, reduces the overall duty cycle

$$\text{duty cycle} = (tON/(tON + tOFF)) \text{ (Eq. 4)},$$

reducing the converter's power output.

As the input voltage is lowered, a larger flyback voltage appears across the inductor **L1C** during tOFF, discharging it more rapidly. Reducing tOFF serves to increase the overall duty cycle (Eq. 1), boosting power output, tending to offset the effect of the lower supply voltage (see Fig. 4).

More particularly, tOFF is approximated by

$$tON^* \mathbf{Vcc} / (Vout + Vf(\mathbf{D2C}) - \mathbf{Vcc}) \text{ (Eq. 5)}.$$

Note that the numerator in this expression increases with **Vcc**, whereas the denominator term decreases. Both serve to increase tOFF with increasing **Vcc**, stabilizing the output power.

A second **Vcc**-related compensation is simultaneously present, operating as follows: as **Vcc** falls the voltage across tON timing resistor **R3C** is reduced, causing it to charge tON timing capacitor **C2C** more slowly. tON is extended, allowing inductor **L1C** to charge to higher currents, and the converter's output power increases, opposing the drop in its supply voltage.

Fig. 4. graph 402 shows actual input-current vs. input-voltage performance of a prototype of the invention; Fig. 6c illustrates the current waveform in inductor **L1C**.

It can be seen that changing the off-timing capacitor **C1B** (Fig. 1B) to **Cinf** (Fig. 1C) creates a new, compensated topology whose output power increases approximately linearly with input voltage, in contrast with traditional circuits whose output powers increase exponentially or in uncontrolled fashion under the same conditions.

FURTHER COMPENSATION

If desired, a voltage divider network from **Vcc** to ground, with the divider tap connected to **C2C**, with or without non-linear elements such as diodes, may also be employed instead of a simple timing resistor **R3C**. Using a divider serves to decrease the effective voltage applied to the resulting effective timing resistor, extending on-time

as **Vcc** decreases (because more time is needed to reach the voltage at which Q1's conduction terminates the on-cycle).

Replacing the on timing-resistor **R3C** with a more complex network, such as a resistive divider, current source, or resistor-diode networks (Figs. 3a-e, respectively) are all effective ways to produce a power output characteristic that is substantially constant despite changes in **Vcc**.

A voltage divider network, with or without non-linear elements such as diodes, may also be employed instead of a simple timing resistor.

BUCK-BOOST

In the case where **Vcc** is greater than the forward voltage of the LED **D2C**, the grounded terminals of **C3C** and **D2C** can be instead connected to **Vcc**. This allows the converter to be used in multi-cell and lithium-cell applications.

ALTERNATE TIMING CURRENT GENERATORS

It is possible to tailor the invention's output-power vs input-voltage response, which might be desired, for example, to give warning of a depleted battery, or to provide the most constant possible light intensity if that is desired. Figs. 3a-e depict alternative timing current networks to replace timing resistor **R3C** of Fig. 1C.

Fig. 3a. shows a diode in series with a resistor, with the combination shunted by a second resistor. The diode serves to provide an offset voltage below which the timing current is very small, and to increase the timing current more rapidly about this voltage than would would be supplied by a simple resistor. The shunt resistor is optional, and provides a minimum current proportional to **Vcc**. It is thusly possible to create a timing current that reduces the converter's overall input current with increasing **Vcc**, resulting in constant (or even increasing) power output; i.e., constant LED brightness.

Fig. 3b. and 3c. depict current sources: the constant current source of 3b. produces constant tON and a power output that varies linearly with **Vcc**. The **Vcc**-dependent current source of Fig. 3c. produces a tON that varies inversely with **Vcc**, yielding constant power output.

Fig. 3d. depicts two switchable timing resistors in series with a diode, which produces a converter with two switch-selectable output powers that are stabilized over variations in **Vcc**.

Fig. 3e. depicts a variable resistor in series with a diode, providing a compensated, variable power source for dimmable lighting applications.

Obviously these are not the only possible timing current generators, but are merely examples intended to show the flexibility and ease of adjustment of the present invention.

REVIEW

From the description above, a number of advantages of my converter become evident:

(a) The present invention achieves output power control without added feedback circuitry or current-sensing schemes required in prior-art circuits. This is possible because the flyback-control mechanism of the instant invention provides inherent feedback, together with a simple timing current generator that abbreviates "on" time with increases in supply voltage.

(b) A further advantage is that the present invention's output power versus input voltage characteristic is easily compensated by employing alternate timing current generators, e.g. Figs. 3a-e, to supply a customizable result.

(c) Also, unlike continuous-mode prior-art circuits, the present invention switches "on" at the zero-current point, improving efficiency.

(d) Flyback control of off-time guarantees that the invention will not enter a runaway continuous-mode region of operation as is inherent with the prior art. The instant invention's topology ensures that off-time will *increase* with increasing supply voltages. By contrast, the conventional & prior-art multivibrator converter's off-times *decrease* with increasing supply voltage, permitting less of the inductor's energy to be discharged and increasing the possibility for runaway, undesirable saturation of the inductor, and/or overcurrent in the load or switching transistor.

(e) The output power of the present invention is substantially stabile over variations in input voltage. Fig. 4 curve 402. shows the performance of the instant invention of Fig. 1c, whose input current is substantially stable, operation is highly efficient, and input power varies over a ratio of 2.6:1 over the input voltage range, a 13-fold improvement when compared to the prior art curve **401**.

(f) If desired, even greater output stability can be produced using alternate timing current generators (Fig. 3a-e) to produce the desired output power versus input voltage characteristics.

(g) A further advantage of the instant invention is that its output can be readily controlled by changing the timing current flowing into a single node (i.e., Fig. 1c, junction of **Q1C**(base) and **C2C**). This makes the circuit suitable for applications where more than one power output level is needed, such as in a flashlight with multiple brightness levels. Ordinary multivibrator circuits have *two* independent time constants and so cannot be as easily adjusted.

Conclusions, Ramifications, and Scope of Invention

In summary, changing one component, **C1B** (Fig 1C), in a prior-art configuration, produces a new circuit and functionally different topology, with profoundly different and highly desirable characteristics.

The new topology employs a new mode of operation with profoundly different characteristics, and possesses a number of important advantages. Among these advantages are dramatically improved stability of output over variations in input voltage, insensitivity to component tolerances, freedom from runaway, and the ability to control the circuit's output power via a single-point adjustment. Although this invention has been set forth as an ideal driver for light-emitting diodes, the invention is useful as a general-purpose d.c.-to-d.c. converter with numerous diverse applications that will be apparent to those skilled in the art.